

# $\pi^0$ and the T2K Experiment

**Benjamin Still<sup>1</sup>, on behalf of the T2K collaboration.**

Queen Mary, University of London  
b.still@qmul.ac.uk

**Abstract.** The Tokai to Kamioka neutrino oscillation experiment aims to determine the third and final lepton mixing angle  $\theta_{13}$ , through a measurement of the sub-dominant oscillation  $\nu_\mu \rightarrow \nu_e$ . The oscillation is a maximum as  $\nu_\mu$  travel 295 km from the near detectors to the far Super-Kamiokande detector. Single  $\pi^0$  production from neutral current (NC1 $\pi^0$ ) neutrino interactions are a significant background to  $\nu_e$  events in water Cherenkov detectors such as Super-Kamiokande. To reduce this background, the off-axis ND280 near detector contains water target regions to determine the cross-section of such NC1 $\pi^0$  events. Here, I discuss the status of the detectors and tools in preparation for physics data taking.

## 1. Introduction

Neutrino oscillation, first confirmed by the Super-Kamiokande (Super-K) experiment in 1998[1], is a young field of particle physics. It is about to enter the age of precision measurements with a new generation of neutrino beam and reactor experiments closing in on the third and final unmeasured lepton mixing angle,  $\theta_{13}$ .

The current direct upper limit of this small mixing angle is set by the CHOOZ reactor experiment, 90% C.L. shown as the shaded region of Fig. 1(a)  $\sin^2 2\theta_{13} < 0.19$ [2] (at  $\Delta m_{23}^2 = 1.9 \times 10^{-3}$  eV), which is consistent with zero within errors. There is a hint, however, of a non-zero value for  $\theta_{13}$ [3] from global fits to all neutrino oscillation data; solar, atmospheric, reactor and accelerator. If  $\theta_{13} \neq 0$  then neutrino oscillation experiments will have the task of determining the level of CP violation in the lepton sector.

The Tokai to Kamioka (T2K) experiment is the first of the new generation of super-beam neutrino oscillation experiments. T2K uses the worlds most powerful man-made beam of neutrinos, generated at the Japan Proton Accelerator Research Center (J-PARC) in Tokai, Ibaraki Prefecture, Japan. T2K will have a sensitivity to  $\sin^2 2\theta_{13}$  an order of magnitude better than the CHOOZ limit. The beam is sampled by a suite of near detectors at 280 m from the beam target station; profiling the beam composition, direction and energy spectrum. Different detectors within the suite aim to constrain errors on key systematic sources to within 10%, Fig. 1(b). The neutrinos then travel 295 km across Japan to be sampled again by the refurbished and upgraded Super-Kamiokande detector.

## 2. Measuring $\theta_{13}$ : $\nu_\mu \rightarrow \nu_e$

The T2K neutrino beam is composed of more than 99%  $\nu_\mu$ , the majority of which oscillate to  $\nu_\tau$  over the 295 km journey thanks to a near maximal mixing  $\theta_{23}$ . The sub-dominant oscillation

<sup>1</sup> Supported by the EU grant No. 207282-T2KQ MUL

of  $\nu_\mu$  to  $\nu_e$  is driven by the  $\theta_{13}$  mixing angle, as seen in the simplified three neutrino oscillation probability relevant to T2K:

$$\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) \simeq & \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta \\
& \pm \alpha \sin 2\theta_{13} \cos \theta_{13} \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta \\
& - \alpha \sin 2\theta_{13} \cos \theta_{13} \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \sin 2\Delta \\
& + \alpha^2 \cos^2 2\theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta,
\end{aligned} \tag{1}$$

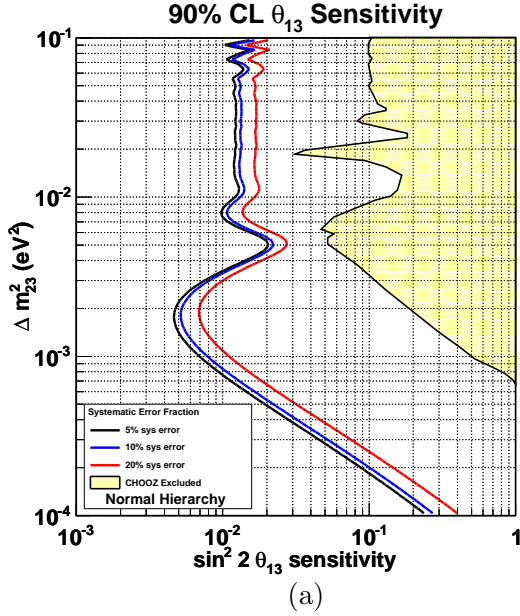
where  $\alpha \equiv \Delta m_{21}^2 / \Delta m_{31}^2$  and  $\Delta = \Delta m_{31}^2 L / 4E$ .

The neutrino energy spectra are determined at both near and far detector from Charged Current Quasi-Elastic (CCQE) events. These events are selected with high efficiency and are theoretically well understood; a tree level two body interaction, with just a recoil nucleon and relevant charged lepton in the final state.

There are two major backgrounds to  $\nu_e$  appearance at Super-K. The first is the small intrinsic  $\nu_e$  content of the beam produced at J-PARC, discussed elsewhere in these proceedings [4]. The second arise from the production of a lone  $\pi^0$  from neutral current  $\nu_\mu$  interaction ( $\text{NC}1\pi^0$ ), discussed in the next section.

### 3. $\text{NC}1\pi^0$ Background

Super-K has excellent discrimination between minimally ionizing (MIP) and electro-magnetically (EM) showering particles. This allows accurate determination of charged current  $\nu_\mu$  and  $\nu_e$  event rates respectively. CCQE signals require the detection of a single particle of either MIP or EM showering type.



Systematic Source	Limit	Detectors
Beam Direction	< 1 mrad	INGrid ND280 MuMon
$\nu$ Energy Spectrum	< 10 %	ND280 NA61 INGrid
Beam $\nu_e$ Component	< 10 % (relative)	ND280 NA61
$\text{NC}1\pi^0$ x-sec	< 10 %	ND280

**Figure 1.** (a) T2K sensitivity to  $\theta_{13}$  at the 90% confidence level as a function of  $\Delta m_{23}^2$ . Beam is assumed to be running at 0.75 MW for  $5 \times 10^7$  s, using the 22.5 kton fiducial volume SK detector. 5%, 10% and 20% systematic error fractions are plotted. The yellow region has already been excluded to 90% confidence level by the Chooz reactor experiment. The following oscillation parameters are assumed:  $\sin^2 2\theta_{12} = 0.8704$ ,  $\sin^2 2\theta_{23} = 1.0$ ,  $\Delta m_{12}^2 = 7.6 \times 10^{-5}$  eV<sup>2</sup>,  $\delta_{CP} = 0$ , normal hierarchy. (b) T2K target systematic errors and near detectors involved.

$\sin^2 \theta_{13}$	Backgrounds			Signal
	$\nu_\mu$ Induced	Beam $\nu_e$	Total BG	
0.1	10	16	26	143

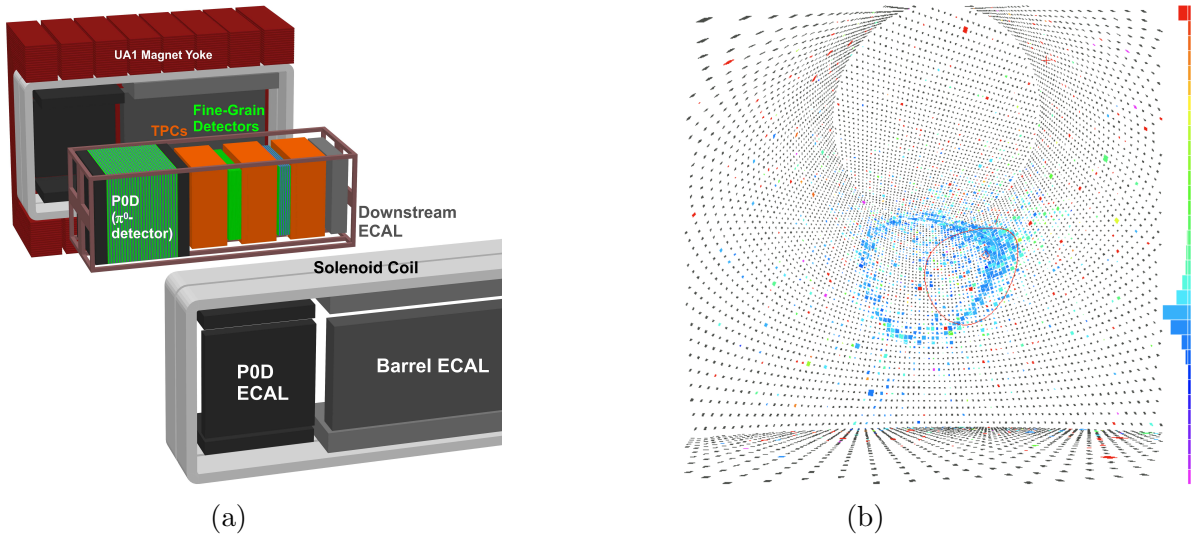
**Table 1.** Expected reconstructed events at Super-K for the projected lifetime of the T2K experiment,  $0.75 \text{ MW} \times 5 \times 10^7 \text{ s}$ .

A  $\pi^0$  decays into two photons, which should show as two EM showering type particles in Super-K. Issues arise if just a single photon is observed, producing a signature indistinguishable from a single electron, a signature of a  $\nu_e$  CCQE interaction. This may occur if one photon is of insufficient energy to pair produce particles above the Cherenkov threshold of Super-K. Such background may also arise if both photons signals overlap posing as just a single EM showering particle.

Super-K has a collection of algorithms in place to minimise the latter: a second Cherenkov ring search and invariant mass reconstruction, as seen in Fig. 2(b). Despite this reduction, the remaining events still pose a significant background to the small expected number of oscillated  $\nu_e$  events.

Over the projected lifetime of the T2K experiment ( $0.75 \text{ MW} \times 5 \times 10^7 \text{ s}$ ), assuming  $\sin^2 \theta_{13} = 0.1$ , just below that of the current limit, we expect 143  $\nu_e$  appearance signal events at Super-K, see Table 1. As we approach the sensitivity limit of the experiment, the number of signal events scales almost linearly, so just 14 at a value of  $\sin^2 \theta_{13} = 0.01$ .

Over the same lifetime a total of 26 irreducible background events are expected; 10 from  $\nu_\mu$  induced NC1 $\pi^0$  events and 16 expected intrinsic beam  $\nu_e$ , Table 1. One can see, therefore, that the sensitivity of T2K to the value of  $\theta_{13}$  is heavily dependent on our understanding of the  $\nu_e$  backgrounds. It is the goal of the ND280 off-axis near detector to measure the cross-section of NC1 $\pi^0$  and intrinsic beam  $\nu_e$ .



**Figure 2.** (a) Schematic of the ND280 near detector. (b) A recovered single  $\pi^0$  from the K2K neutrino beam [5], with second ring fitted.

#### 4. Measuring $\pi^0$ at ND280

The ND280 off-axis near detector is a collection of specialised sub-detectors all housed within the refurbished UA1 magnet which provides a uniform dipole field of 0.2 T. The downstream tracker region, consisting of time projection chambers (TPCs) and finely grained plastic scintillator detectors (FGDs) are discussed further elsewhere [6].

In the most upstream end of the ND280 inner basket of the detectors is the Pi-Zero Detector (P0D), a plastic scintillator tracking detector. The P0D has a large fiducial mass, which also include bladders of water, to yield large numbers of neutrino interactions. Triangular scintillator bars provide accurate shower pointing. The bladders of inactive water will be filled or emptied at various stages of data taking, allowing the determination of the relative event rate of  $\text{NC}1\pi^0$  production on water.

Over the same lifetime of the T2K experiment ( $0.75 \text{ MW} \times 5 \times 10^7 \text{ s}$ ) the P0D expects to successfully reconstruct and select over 9000  $\text{NC}1\pi^0$  events. With projected systematic uncertainties summing to less than 8% the P0D is envisaged to perform its task of understanding the  $\text{NC}1\pi^0$  interaction rate to better than the 10% target uncertainty.

A complementary measurement of  $\text{NC}1\pi^0$  will also be made by the tracker region of the ND280, at reduced statistics. The electromagnetic calorimeters (ECals) surround the tracker region, catching and containing escaping photons from decaying  $\pi^0$ . This complementary measurement will reduce the associated systematic errors.

#### 5. Status and Conclusions

The hardware upgrade of Super-Kamiokande IV is complete and new techniques of  $\pi^0$  and electron discrimination are in development. All central sub-detectors of the ND280 near detector, including the P0D, have been commissioned and are taking data in unison. The electromagnetic calorimeters (ECals) surrounding the inner detector regions will be installed this summer during a scheduled beam shutdown, which will complete the ND280 detector.

The INGrid near detector is performing well, monitoring the beam position to better than the required 1 mrad. The J-PARC neutrino beamline itself is currently supplying protons to the target steadily at around 40 kW.

Physics analyses are in heavy development in every area, including  $\pi^0$  event selection. First results of event rate and vertex positions are expected this summer 2010.

#### Bibliography

- [1] Fukuda, Y. et al. (1998) *Phys. Rev. Lett.* **81**, 1562–1567.
- [2] Apollonio, M. et al. (1999) *Phys. Lett.* **B466**, 415–430.
- [3] Fogli, G. L., Lisi, E., Marrone, A., Palazzo, A., and Rotunno, A. M. (2008) *Phys. Rev. Lett.* **101**, 141801.
- [4] George, M. (2010) *Proceedings of the 25th Lake Louise Winter Institute*.
- [5] Barszczak, T. <http://www.ps.uci.edu/~tomba/sk/tscan/k2k-pi0/>.
- [6] Mahn, K. (2010) *Proceedings of the 25th Lake Louise Winter Institute*.